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Soil Moisture Response to Spraying Big Sagebrush: A Seven-Year Study and Literature Interpretation

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Treating sagebrush with 2,4-D reduced the fall soil moisture deficit of a mountain big sagebrush stand, based on the surface 183 cm of soil. Depletion from sprayed plots exceeded that from undisturbed sagebrush vegetation in the surface 61 cm of soil because of increased grass density. Percent reduction in fall soil moisture deficit is given by the relationship $y = 35.57e^{-0.259t}$, where t is the number of years since treatment. Current study results resolve many of the inconsistencies of previous soil moisture studies.

Keywords: *Artemisia tridentata,* sagebrush control, soil moisture deficit.

ERRATA

The equation defining the percent reduction in fall soil moisture deficit is in error. The relationship $y = 35.57e^{-0.259t}$ should read $\underline{27.46}^{-0.259t}$. The incorrect equation is given in the abstract above, in the Highlights section on page 1, right-hand column, on page 10, right-hand column, and in the four bibliocards provided at the end of this text.

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Highlights

Based on measurements in the surface 183 cm of soil, the fall soil moisture deficit of a mountain big sagebrush stand was reduced 19%, 16%, 12%, and 8% in the first, second, third and fifth year, respectively, following sagebrush control with 2,4-D. Depletion from sprayed plots exceeded that from undisturbed sagebrush vegetation in the surface 61 cm of soil, however, because of increased grass density. Consequently, overall treatment gains were realized between a 91- and 183-cm soil depth, and these gains accrued while vegetation was actively growing, not uniformly throughout the summer. The percent reduction in fall soil moisture deficit is given by the relationship $y = 35.57e^{-0.259t}$, where t is the number of years since treatment. Current study results resolve many of the inconsistencies of previous soil moisture studies that stemmed from not measuring moisture content through the entire rooting zone of big sagebrush.

Controlling big sagebrush (*Artemisia tridentata*) as a range improvement practice not only increases usable forage production — the purpose of the practice — but triggers other ecologic and hydrologic changes as well. These changes have received little attention compared with the well-documented response in usable forage production. For example, after sagebrush is controlled, soil water formerly used by sagebrush becomes available for transpiration by residual onsite vegetation, for evaporation, or enters the groundwater system. The hydrologic question of how, or if, big sagebrush control influences streamflow quality, quantity, or timing has not been resolved. Neither is there a consensus in the literature concerning the simpler question of how sagebrush control alters soil moisture dynamics.

This Paper has the dual purpose of (a) presenting the results from a study in which the soil moisture regime of a sprayed big sagebrush stand is compared with an undisturbed sagebrush stand over a 5-year posttreatment period, and (b) interpreting results of previous soil moisture studies in terms of the current study.

Literature Review

The big sagebrush complex, as separated into three subspecies by Beetle (1960) and Beetle and Young (1967), has distinct ecologic and hydrologic requirements (Winward 1970). In Wyoming, for example, mountain big sagebrush (*A. t. vaseyana*) is found above 2,100 m where it occupies sites that have well-developed soils and favorable moisture relations. On the other hand, Wyoming big sagebrush (*A.t. wyomingensis*), found mostly between 1,500 and 2,100 m, is indicative of dry, shallow soils and less precipitation. Consequently, sagebrush identification to subspecies is important since the nature of the soil moisture response following control may be quite different.

The thin-layer chromatography procedure described by Brunner (1972) is one means of identifying big sagebrush to the subspecies level. Stevens and McArthur (1974) devised a simpler field technique in which the color of a water extract made from fresh or dried leaves, seeds, or broken stems, is observed under longwave, ultraviolet light.

Soil moisture measurements must extend through the sagebrush root system to fully evaluate how control affects the soil moisture regime. Individual plants growing on good sites with well-developed soils have a dense network of shallow roots beneath the canopy, which are underlaid by a deeply extending taproot or lateral roots which branch off the taproot. Tabler (1964) found about 62% of the root length of mature mountain big sagebrush plants was located in the upper 60 cm of soil. Plants had a lateral spread of 152 cm and maximum rooting depth of 183 cm. Sturges (1977) measured root density about mountain and Wyoming big sagebrush plants growing on sites in close proximity, and found about 85% of the root weight for both subspecies was located in the upper 61 cm of soil. The Wyoming subspecies had roots extending between 122 and 152 cm deep, but mountain sagebrush roots penetrated to between 183 and 213 cm. The shallower rooting depth of Wyoming big

sagebrush was attributed to limited soil water availability. Wind scoured sufficient snow from the site to restrict appreciable recharge to a 91 cm depth, while soil at the mountain sagebrush site was fully recharged beyond 244 cm.

Immature plants quickly develop an extensive root system. Sagebrush plants 7 or 8 years old may have a rooting depth in excess of 152 cm and a lateral spread of more than 104 cm (Cook and Lewis 1963). Soil factors strongly influence the morphology of the root system. Rooting depths much deeper than 183 cm have been observed on deep alluvium (Kearney et al. 1914). Conversely, an impenetrable layer can restrict roots to a 30 cm depth (Kearney et al. 1914, Goodwin 1956).

Identification of big sagebrush to a subspecies level probably would have been helpful in explaining the wide array of rooting characteristics described by various authors. Such identification would also have been helpful when interpreting results from studies conducted to determine the influence of big sagebrush control on the soil moisture regime. Numerous soil moisture studies have been conducted, but results are quite variable. The failure to extend moisture requirements sufficiently deep to encompass the entire rooting depth of big sagebrush has contributed to variability of conclusions from past studies.

One of the first studies describing how spraying big sagebrush affects soil moisture was conducted by Hyder and Sneva (1956) in Oregon. Plaster of Paris blocks placed 15 and 45 cm deep were used to monitor moisture trends beneath sprayed and unsprayed vegetation. The rate of depletion was faster at both the 15 and 45 cm depths under sprayed vegetation, and this effect became stronger in each of the 3 posttreatment years that measurements were taken. The sagebrush subspecies was not identified, however, and sagebrush roots were not measured.

Sonder and Alley (1961) conducted another early soil moisture study at low and midelevation big sagebrush sites in Wyoming. Soil moisture content was sampled gravimetrically to a 45 cm depth at 15 cm increments the year after spraying at the low-elevation site and 6 years after treatment at the midelevation site. Soil water content in the sprayed area at the lower site was 1.7% higher ($p < 0.01$) for samples collected in July, August, and September when averaged over all sample depths the year after treatment. Treatment differences were not significant 6 years after control, however, at the midelevation site. Sagebrush roots were not studied at either location, and sagebrush was not identified beyond the species level.

Sheets (1968) measured the change in soil water content between successive measurement dates to a 122 cm depth with a neutron probe for 4 years after sagebrush was controlled with 2,4-D at a study site in Wyoming. A treatment effect ($p < 0.05$) was detected between June 11 and July 1 the year after spraying, when moisture use from the unsprayed sagebrush area exceeded that from the sprayed area. Moisture withdrawal was similar for sprayed and unsprayed vegetation during the remainder of the experiment. Sagebrush was not identified to subspecies, nor was its rooting depth determined.

In still another Wyoming study, Tabler (1968) found that evapotranspiration losses from a sprayed mountain big sagebrush stand were reduced 14% the second growing season after treatment compared with losses from undisturbed sagebrush vegetation. Moisture was measured with a neutron probe to a 183 cm depth (through the entire rooting zone of sagebrush) at biweekly intervals. Sufficient water was available from snow to fully recharge soil water content each spring at the 3,000 m study site. All but a small part of the total difference in seasonal depletion developed between June 24 and August 22, while 75% of the treatment difference accumulated in soil between 91 and 183 cm deep. Seasonal water extraction at a 30-61 cm depth from the sprayed area actually exceeded that from the sagebrush stand, reflecting an increase in density of grass roots after treatment. Spraying increased grass production 82% the second posttreatment year.

Shown et al. (1972) also worked in the mountain big sagebrush type, but at a lower elevation and precipitation zone than Tabler's study. Annual precipitation at their Colorado study site was 343 mm, which was not sufficient to completely recharge the soil mantle. Two small watersheds were plowed and planted with beardless bluebunch wheatgrass (*Agropyron inerme*) while two other watersheds remained undisturbed. Seasonal evapotranspiration, determined from gravimetric soil sampling, was about 5 cm less on the grass watershed the year after seeding and 2.5 cm less 2 years after seeding. Evapotranspiration losses were similar for the grassed and sagebrush watersheds in the third and fourth year when the grass stand was fully established. Some differences in moisture use were noted between treatments within the 102 cm moisture measurement zone. Withdrawal in the surface 30 cm of soil was similar for wheatgrass and sagebrush vegetation by the third year, but the grass stand used slightly more water at a 30-61 cm depth while withdrawal by the sagebrush stand was greater below 102 cm. Data were not subjected to

statistical analysis, however. Rooting depth was not determined.

A reduction ($p < 0.01$) in moisture depletion was measured by Sturges (1973) the year a mountain big sagebrush stand in Wyoming was sprayed with 2,4-D. Moisture was measured with a neutron probe to a 183 cm depth by 30 cm increments at biweekly intervals through the growing season. The water content of soil was fully recharged each spring, and moisture measurements extended through the sagebrush root system. Soil water depletion by sagebrush vegetation exceeded that from the sprayed area ($p < 0.05$) from the treatment date (June 23 and 24) through August 4; 83% of the total treatment difference accumulated in soil 61 to 183 cm deep. Both the seasonal timing and depth of treatment differences were similar to Tabler's (1968) findings. Grass production increased 20% on sprayed plots in the treatment year, but total herbaceous production decreased 63% because of the loss of sagebrush herbage.

Moisture content of soil beneath a sprayed big sagebrush stand was higher ($p < 0.05$) at depths of 61 and 91 cm the first and second year after sagebrush was sprayed in a Utah study by Cook and Lewis (1963). However, treatment differences dissipated in the third year. Moisture levels at a 30 cm soil depth were similar for treated and untreated vegetation through the entire study. Young sagebrush plants (7-8 years old) growing at the study site had roots between 152 and 183 cm deep, which suggests that roots of mature sagebrush plants extended at least this deep. The sagebrush subspecies was not noted.

Experimental Site

This study was performed at the Stratton Sagebrush Hydrology Study Area 29 km west of Saratoga, in southcentral Wyoming. The area lies at a 2,225 m elevation and receives about 500 mm of precipitation annually; two-thirds of the total falls as snow. Summer precipitation for the period June 1-September 30 averages 114 mm.

A mature stand of mountain big sagebrush inhabited the study site. Understory vegetation was primarily a bunchgrass mixture comprised chiefly of Idaho fescue (*Festuca idahoensis*) and bluegrasses (*Poa* spp.). The area had been grazed by sheep, but the site was fenced and excluded from grazing during the study.

Fourteen 0.4-ha plots were established in October, 1968 in two strips lying along the contour of a north-facing hillside (fig. 1). The site lies in a moderate snow-catchment zone and there is sufficient snow accumulation to fully recharge soil during snow melt. Soil developed in place from sandstone of the Brown's Park Formation. The A and B horizons are each about 30 cm thick and have a sandy-loam and loam texture, respectively. The C horizon is also a sandy-loam, but contains from 25-90% fine-grained sandstone fragments. Rock fragments are poorly cemented, however, and do not offer a significant barrier to root development or water percolation.

Vegetation Measurements

Changes in the soil moisture regime following sagebrush control largely reflect differences in the growth period or moisture-use zones between replacement vegetation and the original sagebrush stand. Herbaceous production, including the contribution by big sagebrush, was measured annually from 1969 through 1973. Production was measured with an electronic capacitance meter, as Idaho fescue seeds matured in late July, in a manner similar to that described by Currie et al. (1973) and Morris et al. (1976). Metered plots, 30.5×61 cm, were randomly located each year on the 0.4 ha treatment units. Vegetative matter that was clipped to establish the regression rela-

Figure 1.—The 14 study plots were located on a north-facing hillside in two strips.

tionship between meter capacitance and herbage weight was separated into sagebrush, grass, and forb classes. Clipped samples were oven-dried 24 hr at 105 °C before weighing.

Pretreatment data describing the big sagebrush stand were gathered in 1969. Canopy cover was measured by the line intercept method along five randomly located transects on each plot. Transects were 15.25 m long, oriented in a north-south direction. Only that portion of the sagebrush crown containing live leaves was considered. Two of the five intercept transects were utilized for measuring sagebrush density. The plants within a belt 1.3 m wide and extending 7.6 m (0.001 ha) from the south end of the transect were counted. The first sagebrush plant encountered on the transect was severed at ground level so that annual growth rings could be counted; the height and width of the first 15 plants were also measured.

The age structure of the sagebrush stand indicated that it established over a wide time interval, rather than uniformly following a catastrophic event such as fire. About a third of the plants were between 41 and 50 years old, while 57% were between 31 and 50 years (fig. 2). Individual plants ranged in age from 15 to 66 years.

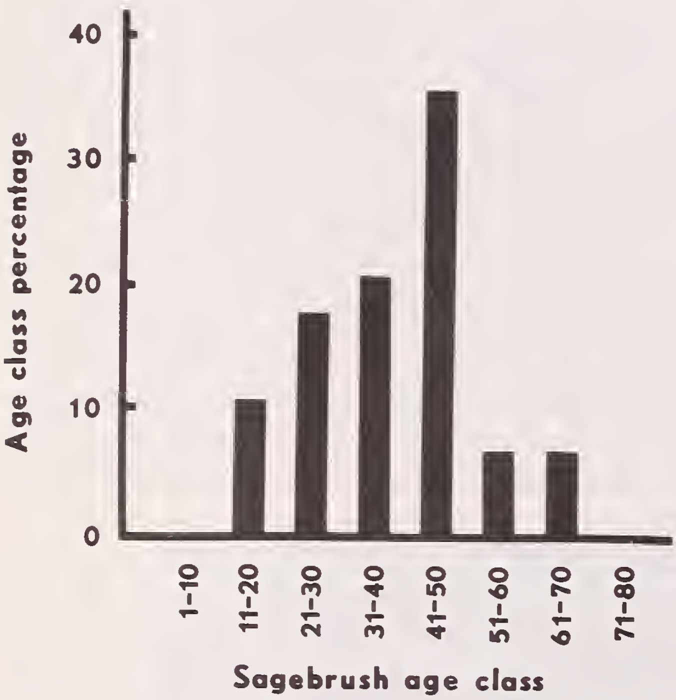

Figure 2.—Age structure of the big sagebrush stand prior to spraying, classified into 10-year periods.

Sagebrush density varied from 15,800 to 84,000 plants/ha on individual plots. Average sagebrush density for the spray treatment was 50,700 plants/ha; density on plots that remained unsprayed was 43,500 plants/ha. Plants on the unsprayed treatment averaged 34.5 cm tall with a crown area of 7.61 dm^2, slightly larger than averages for the sprayed treatment. Crown intercept was 28% on unsprayed plots and 29% on the sprayed treatment. Thus, sagebrush characteristics were quite similar on the spray and nonspray plots prior to treatment.

Total herbaceous production was also similar on the two treatments before spraying. Plots assigned to the spray treatment produced 1,512 kg/ha of oven-dry herbage in 1969 while production for the nonspray plots was 1,334 kg/ha. Big sagebrush contributed 73% of the total, grasses 23%, and forbs 4%.

Soil Moisture Measurements

Soil water content was measured with a neutron moisture meter at four aluminum access tubes on each plot. The tubes were randomly located within the interior 0.2 ha portion of a plot to preclude any possibility of adjacent plots influencing moisture content. Soil water content was measured at six depths per access tube by 30.5 cm increments beginning at a 15-cm depth and extending to 168 cm. Data collected at the four access tubes were used to first calculate average plot moisture content at the six measurement depths; average moisture content for the entire profile was then determined. The 1-min field counts were converted to volume moisture content using a manufacturer-supplied calibration curve except for the 15-cm measurement. A relationship using a polyethylene shield (Pierpoint 1966) was employed to correct field counts for escape of neutrons through the soil surface.

Moisture measurements began in May immediately following snowmelt and continued at about 2-week intervals through September. Vegetation was dormant by the end of September, so the measurement interval encompassed the entire active growth period. The difference between spring and fall soil water contents at the six depths served as the basis for evaluating the effect of sagebrush control on summer moisture withdrawal.

Soil moisture recharge from summer precipitation is largely unaccounted for in this type of evaluation. The method is meaningful in a hydrologic context, however, since the fall soil water deficit must be satisfied before significant quantities of snowmelt water can percolate through the soil mantle. Rainfall during June, July, and August usually did little more than temporarily rewet the surface 46 cm of soil. The change in moisture content between successive sampling dates provided information about moisture-use periods at the six measurements depths through the summer.

During 1969, selected baseline moisture withdrawal and vegetative characteristics were measured to (1) learn if plots assigned to the spray and nonspray treatments had similar water-use characteristics prior to spraying, (2) identify inherent plot variability for other study parameters, and (3) test the adequacy of the experimental design to detect expected treatment differences. Soil moisture measurements continued through the 1970 season when sagebrush was sprayed, and during the first, second, third, and fifth year after treatment.

Spray Treatment

Treatment plots were sprayed with an average of 3.1 kg/ha of 2,4-D on June 23 and 24, 1970. The spray was mixed with water containing a wetting agent, and applied from a truck-mounted spray rig. An excellent sagebrush kill was achieved: more than 95% of the plants were dead in early October of the treatment year. Remaining live plants were hand sprayed in 1971 to achieve as close to 100% control as possible.

Data Analyses

Soil moisture data were analyzed statistically utilizing a split-plot design. The fourteen 0.4-ha plots (whole units) were arranged in seven randomized blocks, while the six measurement depths served as subunits. Treatments were assigned at random within a block. The variance analysis permitted testing for treatment differences as well as for differences in withdrawal between measurement depths, and for a treatment-depth interaction. A variance analysis was made for seasonal change in moisture content based on spring and fall moisture levels, as well as for the change in moisture content between successive sampling dates within a season.

Results

Vegetation Response to Spraying

Herbaceous species responded typically to control with 2,4-D (fig. 3). Forb production was cut in

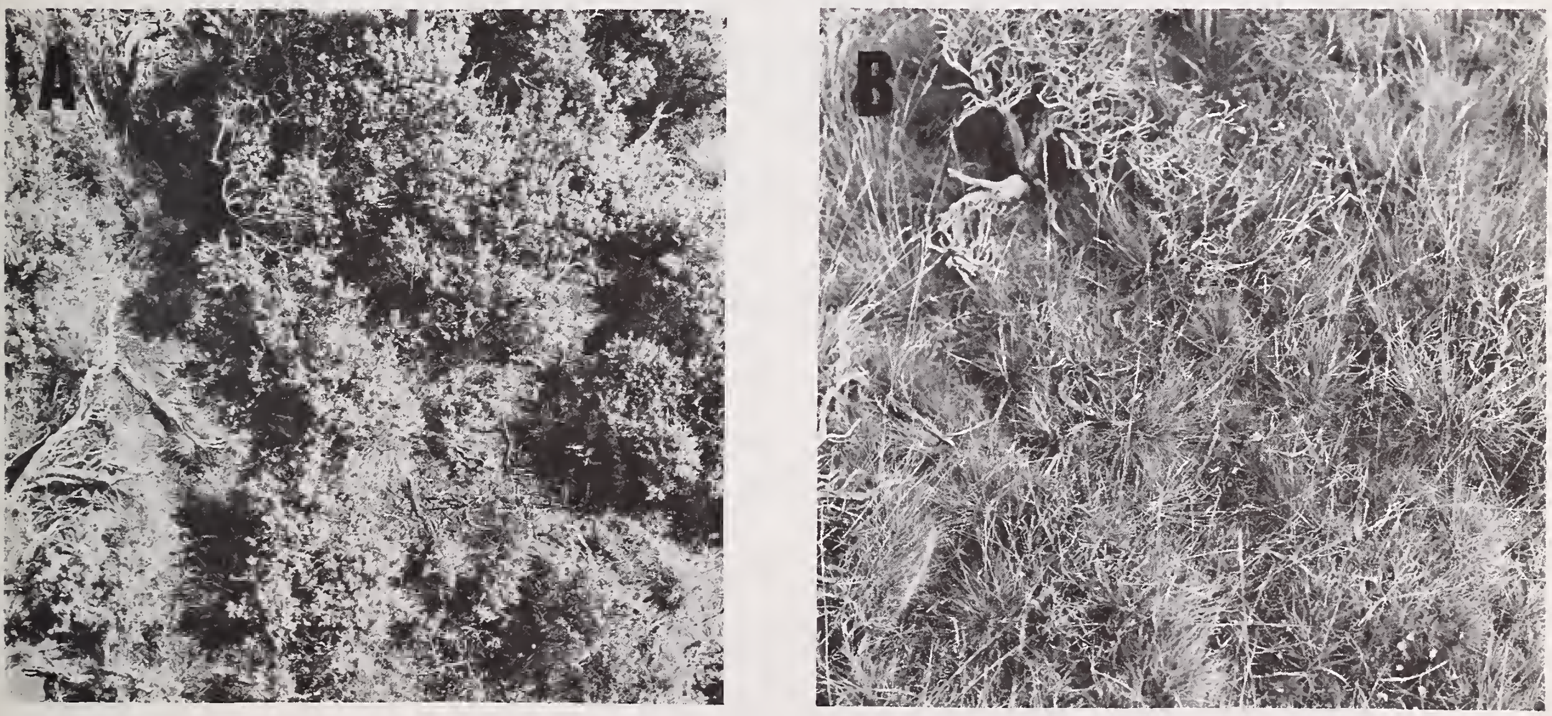

Figure 3.—Appearance of vegetation (A), the year before spraying, and (B) the third year after spraying.

half the year of treatment, and was still suppressed in 1973, the third year after spraying (fig. 4). Grass production doubled on sprayed plots the year after treatment, however, and was 2.6 times larger than on untreated plots in the third year (fig. 4).

How spraying affects total herbaceous production (including sagebrush) is usually not considered when evaluating range improvement projects in the sagebrush type, but this aspect of control has important hydrologic implications. Total herbaceous production on sprayed plots was below that of unsprayed plots in all posttreatment years, since the increase in grass productivity failed to completely compensate for the loss of herbage produced by sagebrush and forbs (fig. 4). Total production on sprayed plots was 29% less than on untreated plots the year after treatment, and was still 23% less in the third posttreatment year.

Soil Moisture

Pretreatment. Both the rate of depletion through the summer and total seasonal depletion were similar on plots assigned to the spray and nonspray treatments in 1969, the year before treatment (fig. 5). Plots assigned to the spray treatment had a deficit of 25.7 cm of water compared to a deficit of 24.6 cm on plots that were not sprayed (table 1).

Variance analyses for change in moisture content between consecutive sampling dates also indicated similar withdrawal patterns on plots assigned to the two treatments. Neither treatment differences nor the treatment x depth interaction term were significant on any measurement date. Depth was consistently significant, however, because moisture withdrawal progressively decreased with increasing soil depth. Total seasonal

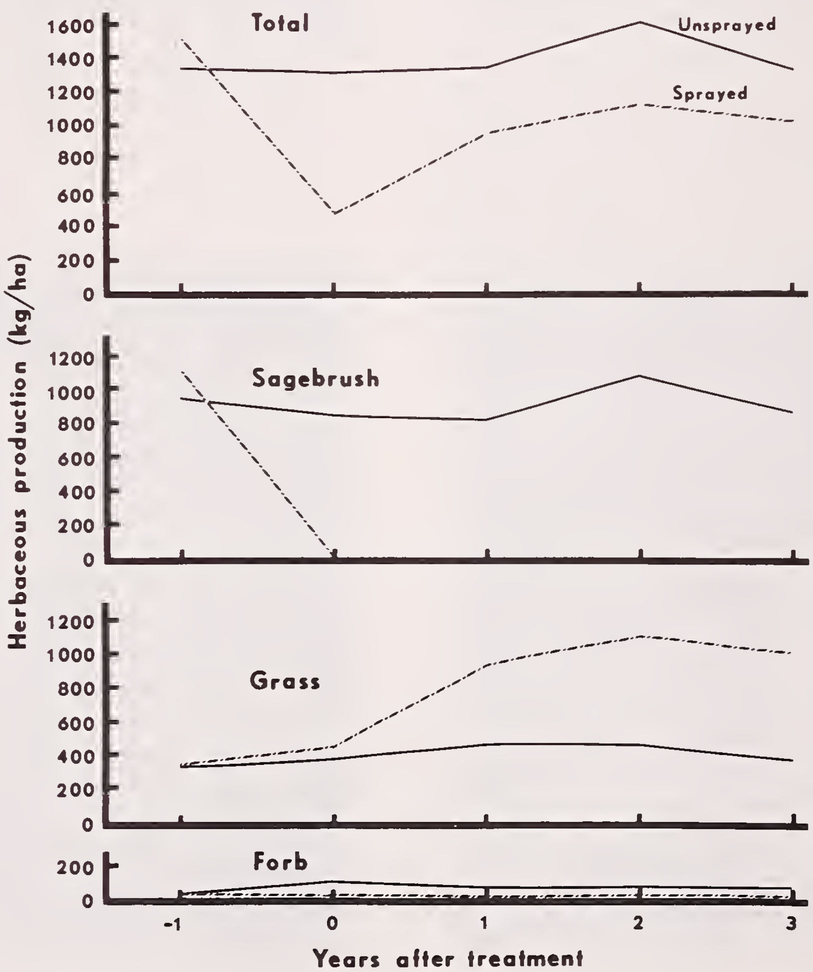

Figure 4.—Total annual herbaceous production and production by forb, grass, and big sagebrush herbage classes, the year before spraying through the third posttreatment year.

Figure 5.—Daily precipitation and water content of soil under sprayed and unsprayed vegetation the year before spraying and 1 and 5 years after spraying.

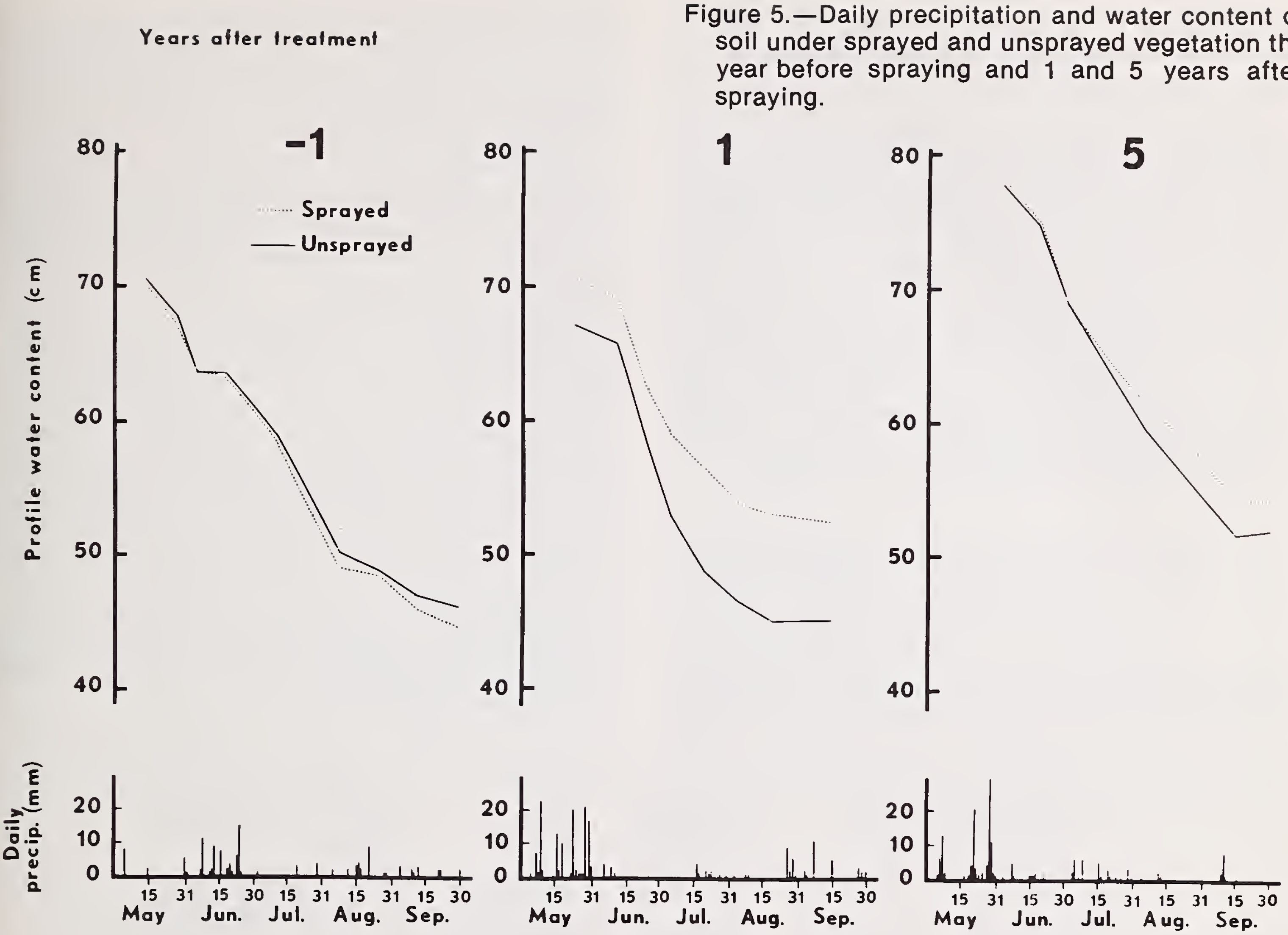

Table 1.—Yearly measurement interval, precipitation, beginning and ending soil water content, and treatment differences for sprayed and unsprayed big sagebrush vegetation, 1969-1975

Year and Treatment	Years after treatment	Measurement period Begin	Measurement period End	Interval precip.	Moisture content Begin	Moisture content End	Moisture content Difference	Treatment difference
				. mm .	. . . .	cm		
1969	-1	05/13	09/29	116				+ 4
Sprayed					70.4	44.7	25.7	
Unsprayed					70.6	46.0	24.6	
1970	0	05/27	09/30	161				[2]-31
Sprayed[1]					68.3	54.1	14.2	
Unsprayed					68.3	47.8	20.5	
Sprayed[1]		06/23	09/30	80	65.8	54.1	11.7	[2]-37
Unsprayed					66.5	47.8	18.7	
1971	1	05/23	09/14	77				
Sprayed					70.6	52.6	18.0	[2]-19
Unsprayed					67.1	45.0	22.1	
1972	2	05/18	10/04	121				
Sprayed					69.1	51.8	17.3	-16
Unsprayed					66.8	46.2	20.6	
1973	3	05/31	10/04	137				
Sprayed					80.5	54.6	25.9	[3]-12
Unsprayed					79.8	50.5	29.3	
1975	5	06/02	09/30	58				
Sprayed					78.2	54.3	23.9	- 8
Unsprayed					77.7	51.8	25.9	

[1]Herbicide was applied June 23 and 24, 1970.
[2]Significantly different at 0.01 level of probability.
[3]Significantly different at 0.05 level of probability.

withdrawal at the six measurement depths (fig. 6) also illustrates the similarity of withdrawal characteristics of treatments prior to spraying.

Treatment year. Moisture depletion was similar for both treatments in 1970 until application of 2,4-D on June 23 and 24. An immediate reduction in the depletion rate was detected. Water withdrawal was reduced 22% in the first 8 d (days) after spraying, and 33% over the next 7 d (Sturges 1973). A treatment difference persisted until August 4, but depletion rates were then similar for the remainder of the summer. The 7 cm difference in recharge requirement that accrued by fall was highly significant. This difference was located primarily in soil below 61 cm (fig. 6).

One year after treatment. A strong treatment effect was evident the year after spraying (fig. 5). The fall recharge requirement of sprayed plots was 4.1 cm less than for untreated vegetation, a difference of 19% ($p < 0.01$). All but a small part of this difference accrued in soil 91-183 cm deep (fig. 6). Seasonal depletion below 91 cm was 67% less on sprayed plots than on unsprayed plots. Conversely, the recharge requirement for sprayed vegetation exceeded that of the sagebrush stand in the surface 61 cm of soil.

Withdrawal on sprayed plots was less ($p < 0.05$) than from the undisturbed sagebrush plots between June 10 and July 20, corresponding to the active growth period. However, the treatment-depth interaction remained significant through mid-September.

Even though total withdrawal was similar after July 20, soil water was utilized differently by depth in the two treatments. Moisture use on sprayed plots came primarily from the surface 91 cm of soil, while sagebrush vegetation utilized appreciable quantities of water from soil 91-183 cm deep after the surface soil dried. These differences in major withdrawal zones reflect the different rooting depths of sagebrush and grass dominated vegetation. Grass production was 939 kg/ha on sprayed plots, about twice as much as on plots where grasses competed with sagebrush for moisture and nutrients.

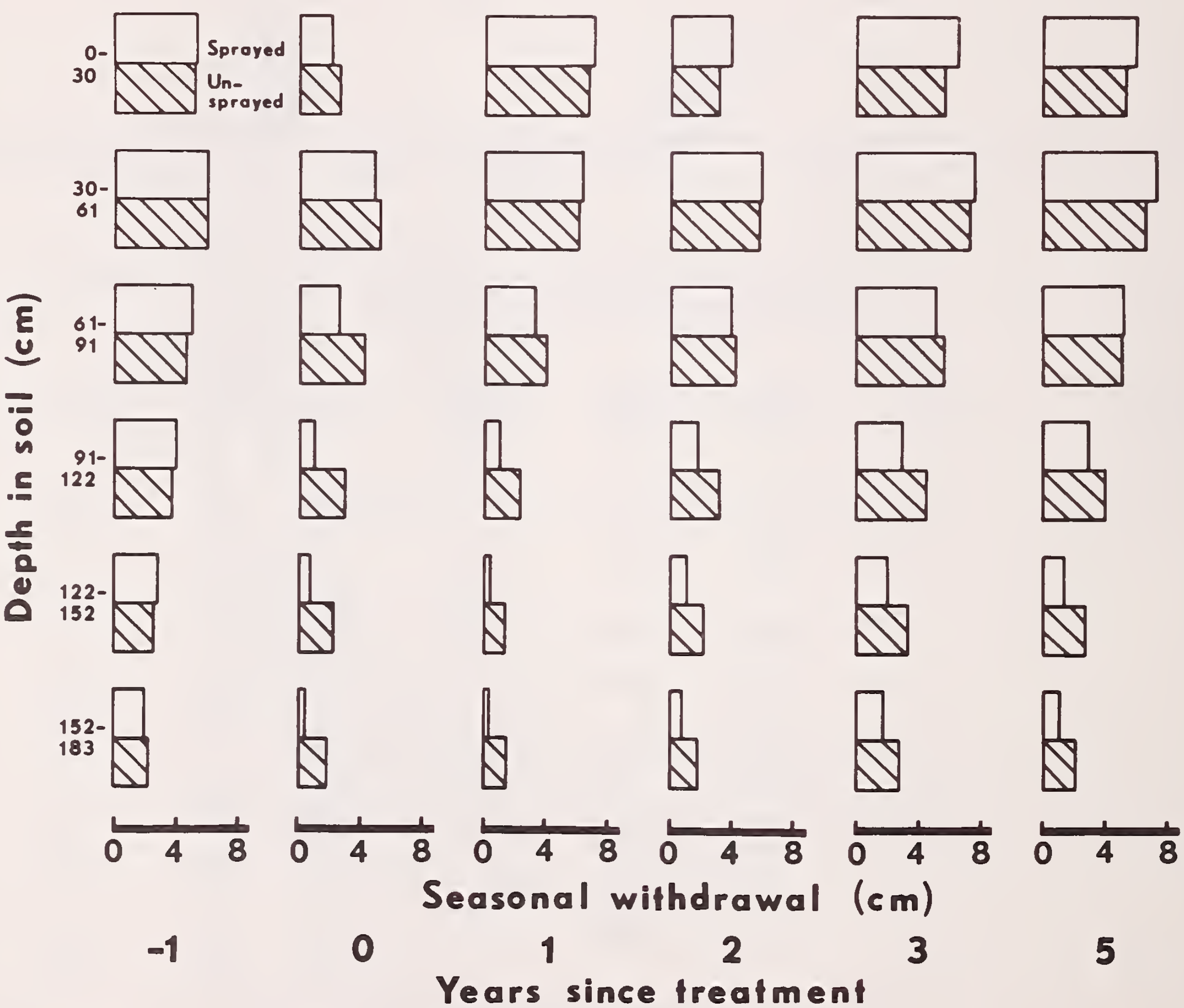

Figure 6.—Seasonal water loss at the six measurement depths under sprayed and unsprayed vegetation the year before treatment through the fifth posttreatment year.

Two years after treatment. The fall recharge requirement of sprayed plots was 3.3 cm smaller than that of sagebrush-covered plots, a difference of 16% ($p < 0.10$); this difference is 3% less than the previous years. Again, the entire difference was realized below a 61 cm depth (fig. 6). Grass production increased to 2.4 times that of unsprayed plots, but total production was 30% below that of unsprayed plots.

Three years after treatment. A definite decay in treatment effect was evident the third year. Although still significantly lower ($p < 0.05$), the fall recharge requirement for sprayed plots was only 12% less (3.4 cm) than that for untreated sagebrush vegetation (table 1). During the summer, moisture withdrawal by sprayed vegetation was significantly less over just one measurement interval, June 25-July 10, compared to a 40-d period the first year after treatment. Withdrawal patterns in the surface 61 cm of soil were about the same each year of study, but a definite reduction in treatment effect was evident in soil 91-183 cm deep (fig. 6). There was a 67% difference in fall recharge requirement the year after spraying at these depths which decreased to a 37% difference in the third posttreatment year.

Five years after treatment. The treatment effect decayed still further between the third and fifth year following sagebrush control (fig. 5). The fall recharge requirement for sprayed vegetation was 2 cm less than that for undisturbed sagebrush vegetation, not a statistically significant difference (table 1). The entire difference accrued in soil below 91 cm deep for the first time in the study (fig. 6). Treated plots did withdraw significantly less moisture over the period July 17-August 5. A significant treatment-depth interaction was present between August 5 and September 15, which indicated that differences in the pattern of moisture use by grass and sagebrush were still present. Data from the last 2 years of study suggested that differences in withdrawal at the 91-183 cm depth stabilized at about a 40% reduction. Depletion was reduced 37% and 40% the third and fifth posttreatment year, respectively.

Seasonal Depletion

Figure 7 illustrates water depletion patterns in soil above and below a 91-cm depth the second growing season after sagebrush control. Vegetation on both sprayed and unsprayed plots utilized surface soil as a major water reservoir through

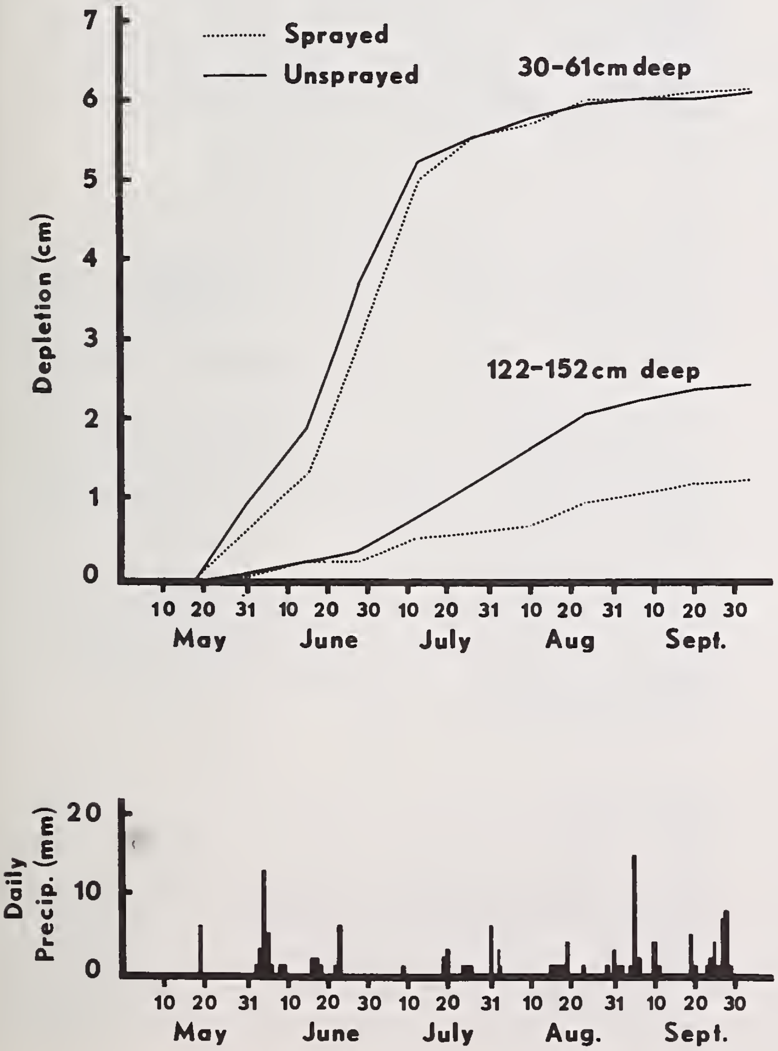

Figure 7.—Water depletion under sprayed and unsprayed vegetation at soil depths of 30-61 and 122-152 cm the second year after spraying.

mid-July. Between June 15 and July 13, a period with little precipitation, the depletion rate in soil 30-61 cm deep was 0.13 cm/d on sprayed plots and 0.12 cm/d on unsprayed plots. By mid-July, soil water content at the 30-61 cm depth was approaching the lower limit of availability, and the depletion rate decreased sharply. Rain in late August and September recharged soil water and largely masked evapotranspiration losses in soil 30-61 cm deep during the interval.

Appreciable water withdrawal from soil 122-152 cm deep was delayed about 6 weeks in comparison to water use from soil 30-61 cm deep for both treatments. Between June 28 and August 24, the withdrawal rate from plots with an undisturbed sagebrush cover was 0.03 cm/d, about 25% as large as that measured earlier in the year from soil 30-61 cm deep. Depletion from sprayed plots for the June 28-August 24 period, however, was only 0.01 cm/d. The depletion rate between August 24 and October 4 was quite uniform, but decreased to an average water loss of 0.009 cm/d for unsprayed plots and 0.007 cm/d for sprayed plots.

Seasonal depletion patterns relate well to vegetation phenology. During late May and early June, grasses and forbs were growing rapidly and utilized moisture primarily from the upper part of the soil mantle. For example, the leaves of Idaho fescue began to elongate rapidly in late May; plants were in anthesis by the end of June, and herbage was curing by late July. Sagebrush stems began to elongate in mid-June. By this time, the deeper roots of sagebrush assumed an active role as available water in surface soil was exhausted by early growth. The deeper sagebrush roots were active through the remainder of the summer. The withdrawal rate in deeper soil decreased in August about the time sagebrush was shedding the large ephemeral leaves produced in early spring when moisture was abundant (Diettert 1938). Sagebrush remained physiologically active after the midsummer leaf drop, however. In 1972, flowers developed in late August and pollination occurred during the first few days of September.

The reversal of treatment effect in the upper and lower parts of the profile previously discussed is obvious in figure 7. Cumulative seasonal withdrawal was almost identical for sprayed and unsprayed vegetation at the 30-61 cm depth in the second posttreatment year. Roots fully occupied shallower soil under both treatments and utilized available moisture to support vegetative development. Conversely, at the 122-152 cm depth, cumulative seasonal depletion by vegetation on sprayed plots was only about half that of the sagebrush stand, a reflection of the difference in rooting depths of grass and sagebrush. Thus, study measurements support the ecological adage that a diverse group of species or lifeforms more fully utilizes site resources than does a single species or lifeform.

Figures 5 and 7 also point out that the difference between treatments did not accumulate progressively through the entire growing season, but rather developed in a relatively short period of time. Indeed, in 1972 not only was the entire treatment difference located below a 61-cm depth, nearly the entire difference developed between June 15 and August 10, when vegetation was actively growing. This phenomenon was also seen the year of spraying when the entire treatment difference accrued between June 23 and August 4 (Sturges 1973).

Predicting Soil Moisture Response

The study provided data to derive an equation relating the magnitude of treatment effect to the number of years since spraying. This equation was developed using data from a site, with soil deeper than 183 cm, that was fully occupied by sagebrush roots and where soil water content was fully recharged each spring. Consequently, the relationship is applicable only for areas with these same basic characteristics. The difference in fall recharge requirement between sprayed and unsprayed sagebrush can be expressed by the relation:

$$y = 35.57\, e^{-.259t}$$

where

y = percent reduction in fall recharge requirement, and

t = number of years since sagebrush control.

The equation is based on information collected the first 5 years after treatment, but should provide a reasonable approximation of treatment effect for longer time periods. For example, the fall recharge requirement for a sprayed sagebrush stand in the 10th year after treatment should be about 3% less than that of the original sagebrush stand; 20 years after treatment, it should only be about 0.7% less.

Discussion

The magnitude and even the direction of the soil moisture response to sagebrush control depends on the depth of treatment evaluation (fig. 8). The family of curves in figure 8 indicates an increasingly large reduction in summer water use

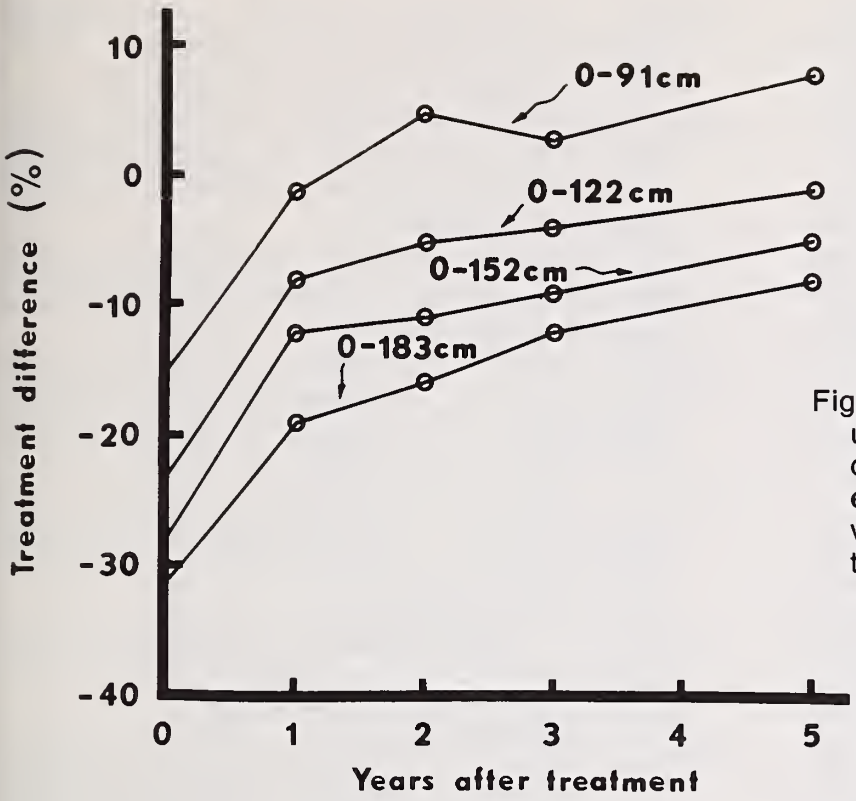

Figure 8.—The effect of depth of soil moisture measurements on the size of the reduction in fall recharge requirement. A negative treatment difference indicates that withdrawal by unsprayed vegetation exceeded withdrawal by sprayed vegetation.

for the spray treatment as the evaluation zone extends below 91 cm. This is because of a reversal in treatment effect in soil above and below a 91 cm depth. Beginning the second year after spraying, water use on sprayed plots exceeded use on unsprayed plots through the surface 91 cm of soil. However, at depths between 91 and 183 cm, water use on sprayed plots was always less than on unsprayed plots. For example, there was a 67% reduction in withdrawal the year after treatment at the 91-183 cm depth which decreased to a 40% reduction in the fifth posttreatment year. Thus, an evaluation of the effects of spraying based on moisture measurements in the surface meter of soil after the second posttreatment year would indicate that spraying increased moisture withdrawal, but by extending the evaluation depth to about 2 m, the opposite conclusion is true.

It is apparent that much of the disparity in literature relating to the effects of big sagebrush control on soil moisture levels can be traced to a failure to measure moisture throughout the sagebrush rooting zone. Tabler (1968) measured soil moisture to a 183 cm depth in an area with characteristics comparable to those of the current study, and found that spraying reduced evapotranspiration 14% the second year after treatment. Most of this difference accrued in soil 91-183 cm deep, and was realized during the active growth period. His findings, then, parallel those of the current study.

Other studies in which moisture measurements were confined to the upper meter of soil failed to fully evaluate the soil moisture effects of sagebrush control. A decline in treatment effect with time in the upper meter of soil was often detected in these studies, however, just as was found in this study. Cook and Lewis (1963), for example, observed no differences in water content of the surface 30 cm of soil between sprayed and unsprayed sagebrush areas, but did find higher moisture levels in soil 30-61 and 61-91 cm deep at the sprayed area the first 2 years after treatment. No treatment differences were found the third year. Similarly, Shown et al. (1972) found that evapotranspirational losses from the surface meter of soil for a beardless bluebunch wheatgrass stand were smaller than losses for mountain big sagebrush the first 2 years after the grass was planted, but the difference disappeared the third year when the grass stand was fully developed.

Another factor adding to confusion in the big sagebrush hydrologic literature is a variable, but not unexpected, soil moisture response related to sagebrush subspecies. Site factors such as effective precipitation and soil development, which influence distribution of the three subspecies, also influence the soil moisture response to sagebrush control. Differences in the fall moisture content between sprayed and unsprayed Wyoming big sagebrush areas would probably be small com-

pared to differences at a wetter site inhabited by mountain or basin big sagebrush. It is probable that some past soil moisture studies were conducted in areas containing the Wyoming subspecies, where spraying would have had a minimal effect on the moisture regime.

Hill and Rice (1963) developed guidelines to describe the soil moisture response to chaparral control in southern California. They stated that, before conversion of chaparral to grass could increase water yield, three conditions must be met: soils must be deeper than 91 cm; the grass stand must be kept free of deep-rooted weed species; and rainfall must be sufficient to replace water used by grasses the previous year.

These conditions are equally applicable to big sagebrush lands. Sagebrush removal will increase soil moisture content only where soils are sufficiently deep that the majority of roots of replacement vegetation lie above soil formerly occupied by sagebrush roots. Precipitation must also be sufficient to recharge soil water beyond the rooting zone of replacement vegetation. Sagebrush control will not have an appreciable effect on soil water regime on those sites with shallow soils where all available moisture is depleted each year. Here, control will merely shift the moisture draft by big sagebrush to replacement species.

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Treating sagebrush with 2,4-D reduced the fall soil moisture deficit of a mountain big sagebrush stand, based on the surface 183 cm of soil. Depletion from sprayed plots exceeded that from undisturbed sagebrush vegetation in the surface 61 cm of soil because of increased grass density. Percent reduction in fall soil moisture deficit is given by the relationship $y = 35.57e^{-0.259t}$, where t is the number of years since treatment. Current study results resolve many of the inconsistencies of previous soil moisture studies.

Keywords: *Artemisia tridentata*, sagebrush control, soil moisture deficit.

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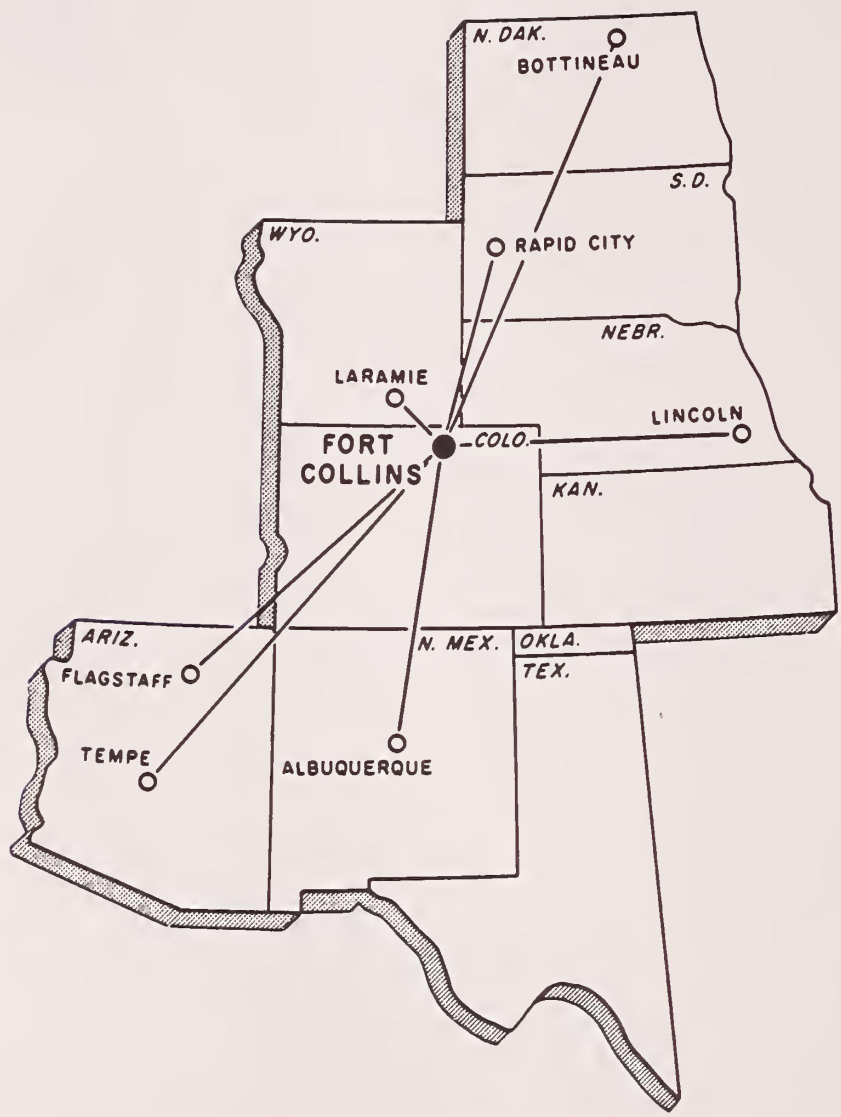
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